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Pulsational variability in proto-planetary nebulae and other post-AGB objects

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Abstract. Light and velocity curves of several classes of pulsating stars have been successfully modeled to determine physical properties of the stars. In this observational study, we review briefly the pulsational variability of the main classes of post-AGB stars. Our attention is focused in particular on proto-planetary nebulae (PPNe), those in the short-lived phase from AGB stars to the planetary nebulae. New light curves and period analyses have been used to determine the following general properties of the PPNe variability: (a) periods range from 35 to 160 days for those of F−G spectral types, with much shorter periods ($\leq$ 1 day) found for those of early-B spectral type; (b) there is a correlation between the pulsation period, maximum amplitude, and temperature of the star, with cooler stars pulsating with longer periods and larger amplitudes; (c) similar correlations are found for carbon-rich, oxygen-rich, and lower-metalicity PPNe; and (d) multiple periods are found for all of them, with $P_2/P_1 = 1.0\pm0.1$. New models are needed to exploit these results.

1. Introduction

After spending most of their life cycle as main sequence stars, intermediate- (2−8 $M_\odot$) and solar-mass stars subsequently evolve through the red giant, asymptotic giant branch (AGB), and planetary nebula (PN) phases on their way to becoming white dwarfs. Stars lose large amounts of mass during the red giant and especially during the end of the AGB phases. Between the AGB and PN phases there is an interval of time when the intensive mass loss has ended and the star is in the post-AGB phase, but when the temperature of the star is too low to photo-ionize the nebula, signaling the beginning of the PN phase. These transitional objects are called proto-planetary nebulae (PPNe) or pre-planetary nebulae [1].

During this PPNe phase the star is luminous (1−10 x 10^3 $L_\odot$) and increasing in temperature from 4000 K (end of AGB) to 30,000 K (start of PN). The study of these objects blossomed after the identification of many candidates in the *IRAS* database. They are found to be stars with spectral types ranging from G to B, surrounded by a dusty, molecular envelope visible in scattered light. Spectral energy distributions showed a characteristic double-peak, with a peak in the visible arising from the reddened photosphere and a peak in the mid-infrared arising from a cool, detached dust shell [2, 3].The timescale for this evolutionary phase is short, $\sim10^3$ years [4, 5].I estimate the number of PPNe confirmed thus far to be about 60 in the Milky Way Galaxy, with a similar number of additional candidates. (The Torun catalog includes these among its post-AGB stars [6]). Detailed follow-up studies of individual objects have yielded information on the chemistry of the gas and the dust [7, 8, 9, 10, 11],the shapes of the nebulae (from *HST* images [12, 13]), the kinematics of the gas [14, 15], and the chemistry of the central stars [16].

In this paper, we will discuss the observed pulsational properties of the central stars of PPNe. Analysis of the pulsational properties (period, amplitude) can yield information on the physical properties (mass, luminosity) and possibly the rate of evolution of the central stars during this transitional phase. Pulsation is known to be a driver of mass loss in evolved stars, and these studies can also shed light on the level of on-going mass loss in the post-AGB phase.

2. Pulsational light curve studies of post-AGB stars

Pulsation is a common feature in post-AGB stars. We will very briefly review the results from post-AGB stars in general in order to provide a context and comparison for the results from the studies of PPNe.

2.1. Pulsation in other post-AGB stars

RV Tauri variable stars are post-AGB stars that have light curves characterized by alternating deep and shallow minima, with light curves ranging in amplitude up to 3 mags. They are of spectral types F−K, with periods of 30−150 days [17, 18]. A recent study shows that many RV Tauri variables possess an infrared excess matching that of a disk, with evidence strongly suggesting that these are all binaries [19].

Other post-AGB stars show light curves that are semi-regular (SRV) or those of Type II Cepheids. Many of these have been found to be in binaries systems [20], with pulsation periods of 50−120 days and amplitudes ranging from 0.1 to 1.5 mags [21, 22].Kiss et al., in their study of these post-AGB stars, found correlations between pulsation amplitude and T_{eff} and between luminosity and T_{eff}, with many of the objects lying within the classical instability strip. Similar objects have been observed in the nearby Large Magellanic (LMC) and Small Magellanic Cloud (SMC) galaxies [23, 24]. Recently Kamath et al. (2016) [25] discovered in the LMC and SMC a new class of post-red giant branch stars; these are dusty, of low mass, and evolved. They are found to significantly outnumber the post-AGB stars in these galaxies, suggesting that some of the SRV and RV Tauri variables in the Milky Way Galaxy (MWG) are also post-RGB rather than the post-AGB stars.

The rare R Coronae Borealis (RCB) stars are thought to also be post-AGB objects that are hydrogen-poor but carbon-rich. In addition to their large drops in brightness (up to 8 mags!), attributed to dust ejections, they also show pulsational variations on the order of 40−100 days with amplitudes of a few tenths mag [26].

2.2. Pulsation in proto-planetary nebulae

Pulsational studies of PPNe have been carried out primarily by two groups. Arkhipova and collaborators at the Sternberg Institute in Moscow have been observing the brighter of these objects since their earliest identification, beginning in some cases as early as 1991. In a series of papers they have presented and discussed light curves of ∼20 PPNe and other post-AGB objects [27, 28, 29].

The second is our group is at Valparaiso University. Observations began in 1994 and have continued to the present time, carried out primarily by supervised undergraduate students. More recently, we have begun observing some fainter and some southern hemisphere PPNe candidates using the SARA (Southeast Association for Research in Astronomy) consortium telescopes in Arizona (0.9 m) and Chile (0.6 m). Presently we are observing ∼50 PPNe and candidates with V = 8−15 mag.

These two studies are complementary, and in some cases we have combined the published data of Arkhipova et al. with ours to increase the data sets for analysis.

3. Results

3.1. Initial results

Initially we analyzed the light curves for 12 C-rich, F−G spectral type PPNe obtained from 1994−2007. All of them were found to vary, with maximum amplitudes ranging from 0.15 to 0.6 mags. The light curves of each changed in amplitude, in some cases resembling a beat phenomenon such as is produced by the combination of two rather similar periods. They each were redder (cooler) when fainter. Period analysis determined that each of them varied in a periodic manner, with periods (P) of 38 to 153 days. Several trends were found in the results. Stars with lower temperatures have longer periods and larger amplitudes, and these decreased monotonically with stars of higher temperatures to a minimum range of values by $T_{\rm eff} \approx 6000$ K (these are shown graphically by Hrivnak et al. 2010 [30], Figs. 18 and 19; Arkhipova et al. 2011 [29] found similar results). This suggested that we were seeing evolutionary effects, and that the trends in this sample display the evolution of a typical C-rich PPNe. The linear relation found for $P-T_{\rm eff}$ over this temperature range of 5000−8000 K, coupled with a post-AGB evolutionary model [31] suggested a decrease in period of ∼2 day per decade. This should be measurable and presented the possibility of measuring evolution in real time and using the results to constrain the evolutionary rate, at least through this range in temperature.

3.2. More recent results

This initial study of C-rich PPNe has been expanded in several directions to include objects that are O-rich, fainter, hotter, or of a differently metallicity. We have also investigated the velocity variations during pulsation. These results are discuss below.

In the analysis of four O-rich, F spectral type PPNe, we were able to increase the temporal baseline by the inclusion of our data up to 2012 and inclusion of data from Arkhipova et al. (2010) [28] and others. This resulted in the determination of a dominant period in each ranging from 41 to 113 days, with additional multiple periods [32]. The maximum amplitudes ranged from 0.14 to 0.21 mag, and thus the periods and amplitudes were in the same range as those of the larger C-rich sample. In all cases, the secondary period was close to the dominant period (±10 %); a similar result was found for two of the previously studied C-rich PPN based on an analysis of an enlarged data set [33].

With the addition of the SARA telescopes and a new CCD at Valparaiso University Observatory, we were able to include some fainter (V = 13−15 mag) and more southerly PPNe candidates. The light curves of a sample of these are shown in Figure 2. The maximum amplitudes range from 0.12 to 0.58 mags. Periods have been determined for 6 of the 9, with dominant periods in the range of 25 to 135 days and multiple periods for each. This study is in progress.

We have also monitored some of the hotter, B spectral type PPNe, both O-rich and C-rich. Again, all of them vary. However, they are found to vary on a shorter time scale, less than a few days, and no periods have been found for the sample. Arkhipova et al. (2006) [34] found similar results. It is suspected that the cadence of our observing, every few days at most, and the low amplitudes combined with multiple periods, make it difficult to detect any periods present in the data. A more intensive study of 2 PPNe observed continuously over several hours on several non-consecutive days revealed some short-term cyclical variability (< 1 day) but no dominant period was detected. This study is in progress.

The use of the *Spitzer Space Telescope* has allowed the identification of many dusty evolved stars in the relatively nearby Large and Small Magellanic Cloud (LMC, SMC) galaxies [23, 24, 35]. These galaxies have lower metallicities, with that of the LMC about 0.4 of the solar metalicity. Mid-IR spectra of these show features that are attributed to O-rich or C-rich dust chemistries. Twenty-two of these were identified as C-rich [36] PPNe. In most cases, OGLE light

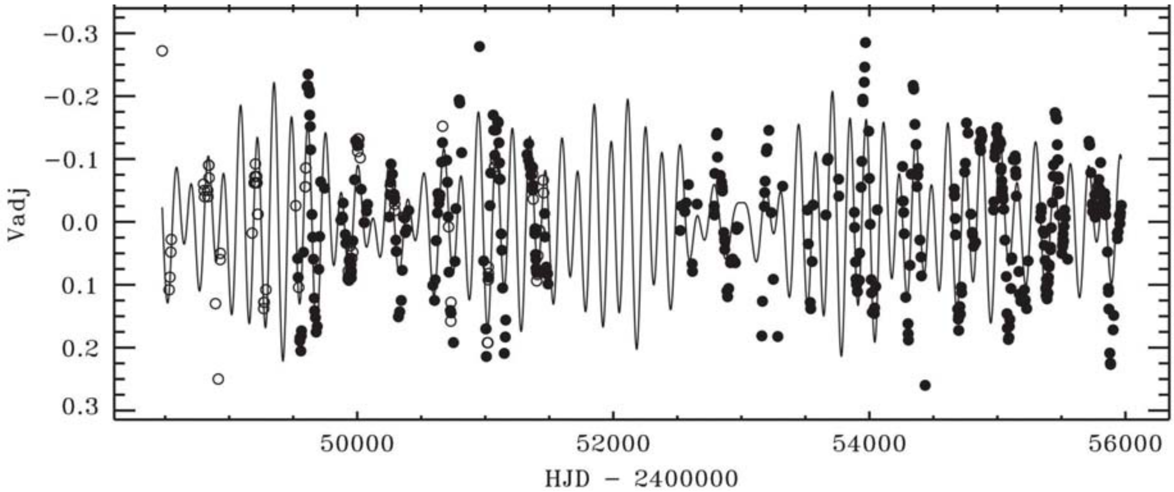

Figure 1. Light curve of IRAS 22272+54435, fitted by four periods, with P_1 = 132 day. The open and filled circles represent data from Arkhipova et al. and from the Valparaiso University Observatory, respectively.

curves were available ranging from 8 to 13 years. For those without OGLE data, MACHO data covering eight years were available to be used. Periods were determined for the light variations in eight of these, with periods ranging from 49 to 157 days, similar to those found in the MWG. Multiple periods were again found, with secondary periods close to the primary periods. These are primarily F stars. For those without period determinations, the variations were of shorter timescale, with some and perhaps all of them being of earlier spectral type. Similar to those in the MWG, there is a trend of decreasing period with increasing temperature and a trend of decreasing amplitude with decreasing period. While the sample of those with period and temperature determinations in the LMC/SMC is small, there is a suggestion that the trend of decreasing period with increasing temperature is offset to lower temperatures or shorter periods than in the MWG [37].

In Figure 3 are plotted these parameter correlations for the various objects discussed above. One can see the general trend of decreasing periods with increasing temperature, as was found for the initial sample of 12 C-rich PPNe. The possible shift for the LMC objects to lower temperatures (or lower amplitude pulsations) can also be seen. Instead of a plot of maximum amplitude with temperature, we have plotted instead the correlation with period since some of the targets do not have temperature determinations. They show that the maximum amplitude decreases steeply with increasing temperature and decreasing period, reaching the low values of 0.15−0.25 mag (V) when the temperature increases to ∼6000 K or the period decreases to ∼120 days (Fig. 3).

3.3. Radial velocity studies

We began a radial velocity monitoring program of the brighter PPNe in 1991 to investigate the possible presence of binary companions. None have been found thus far [38]. However, we did detect periodic variations with periodicities similar to those found in the light curves. This initial study extended to 1995 and then the study was re-initiated in 2007 and is continuing. Seven bright (V=7−11 mag) PPNe have been monitored for velocity variations. Three of these have longer periods (88−132 days) and show consistent light, color, and velocity correlations, with the objects being brightest when hottest and smallest [33]. An example is shown in Figure 4. The pattern is not so clear for the three with short periods, 35−40 days. This may be due to

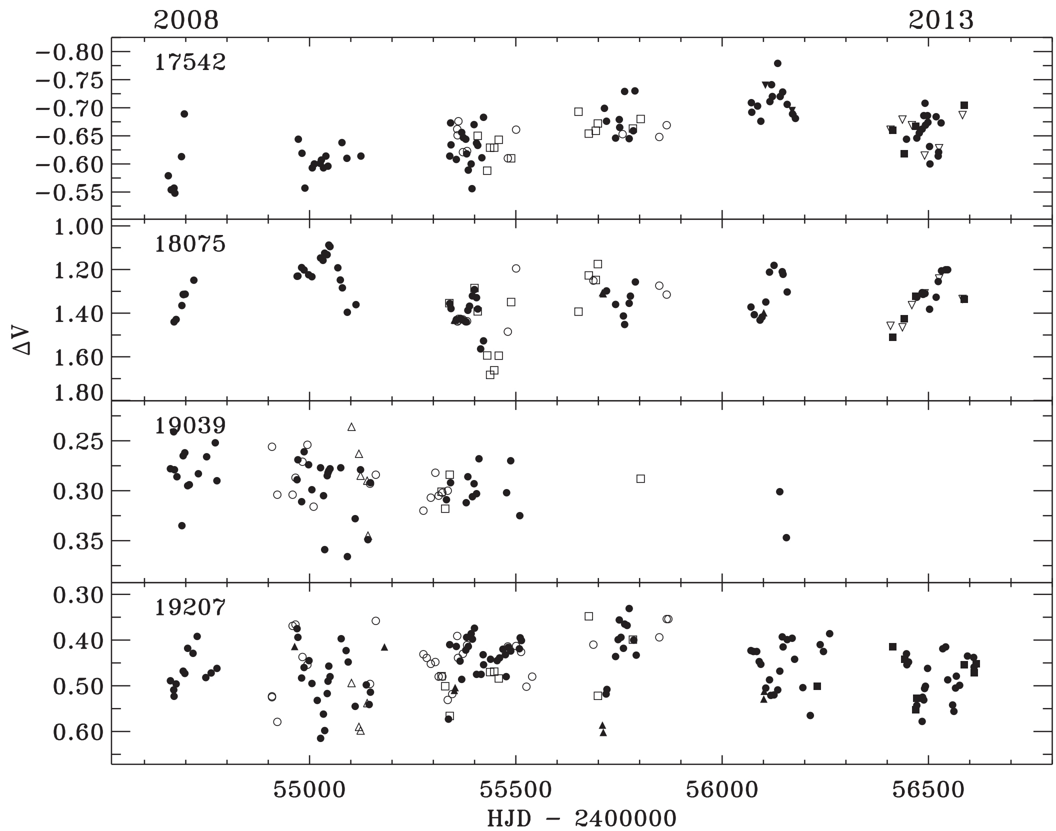

Figure 2. New light curves for a sample of fainter galactic PPN candidates. The different symbols represent data from different telescopes and detectors.

the presence of shocks in these pulsating objects, which lead to line spitting at certain phases and to Hα emission features [39, 40].

4. Discussion & Conclusions

Since the central stars are clearly visible in these PPNe, intensive mass loss has ended by the time that P∼160 days (late-G spectral types). Their spectral energy distributions show that they are surrounded by detached dust shells. By the time that P∼120 days (early-G spectral types), the pulsation amplitudes are small (0.15−0.25 mag) and the pulsation-driven post-AGB mass loss rate is presumably low. It is this post-AGB mass loss that dominates the evolution of the star rather than the fusion of hydrogen at the base of the photosphere.

Fokin et al. (2001) [41] have run non-linear radiative models to fit the light curve of one of the PPN with P∼40 days. The results indicate the way that core mass, luminosity, and temperature effect the period, amplitude, and regularity of the resultant light curves. However, a good fit required an unusually high core mass (0.8 $M_\odot$) and these models would not produce the longer period pulsations. New models are needed to exploit this present wealth of light and velocity curve data.

From the study thus far of about 35 PPN in the MWG and 22 in the LMC/SMC, several patterns have emerged.

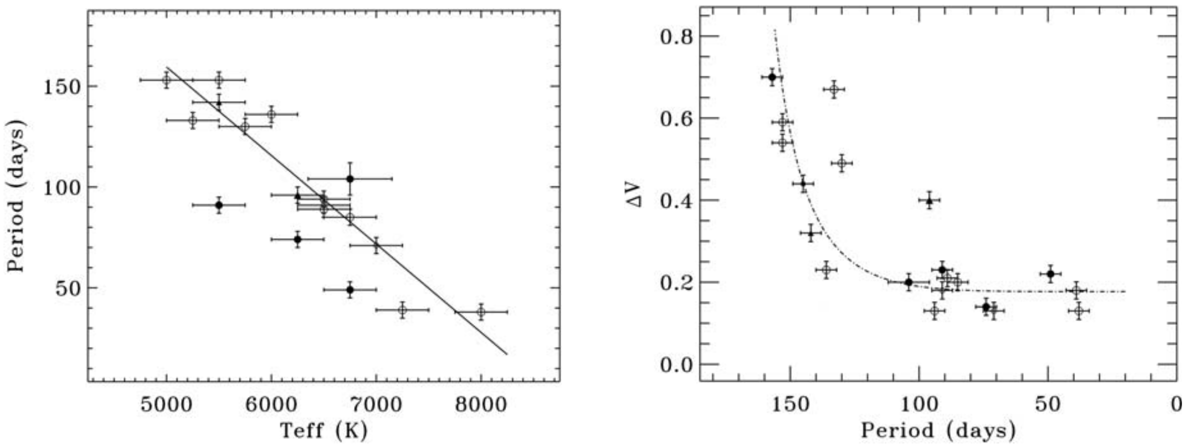

Figure 3. Plots of pulsation period vs. T_{eff} (left) and maximum amplitude vs. pulsation period (right). Plotted are the initial 12 C-rich MWG PPNe (open circles) and 6 C-rich LMC/SMC PPNe (filled circles). The lines represent general trends in the data based on the initial 12 C-rich PPNe. (From Hrivnak et al. 2015a [37].)

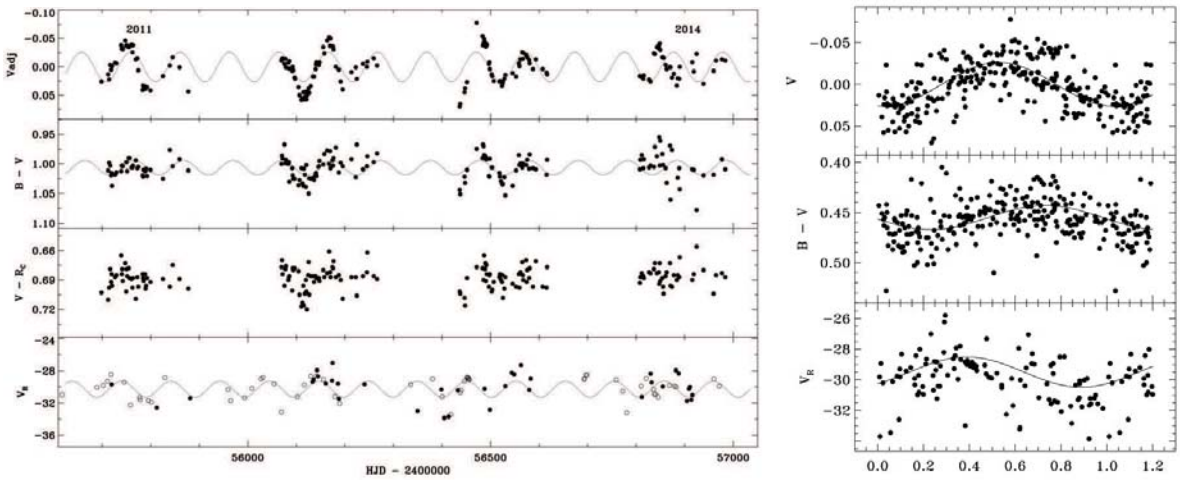

Figure 4. IRAS 18095+2704: (Left) Plots showing (from top to bottom) the normalized V light curve, the B−V and V−R_C color curves, and the radial velocity curve, all fitted with curves based on P = 113 day. (Right) The V, B−V, and radial velocity curves phased with the same period.

1. PPNe with F−G spectral types pulsate with periods ranging from 35 to 160 days. Those that are hotter pulsate on shorter timescales.

2. PPNe have pulsation amplitudes ranging from 0.6 mag (V) for late-G spectral types with P≈150 days to 0.15−0.25 mag for early-F spectral types at P≈40 days. Those at earlier B spectral types vary on timescales of a few days or less.

3. PPNe as an ensemble show evolution to shorter periods and smaller amplitudes, reaching minimum values in amplitude at T ∼ 6000 K and at P ∼ 120 days.

4. PPNe have multiple periods to their pulsations, with the secondary close to the primary period (P_2/P_1 = 1.0±0.1).

5. The evidence for decreasing period with time over the two decades of this study is

not found. This was investigated by dividing the data with longer time strings into subsets and determining their periods. However, the investigation of this effect is complicated by the multiple periods found in the data. It is expected that evidence for this will be found with longer temporal baselines, but it is nevertheless disappointing that it was not found in our two decades of observations.

6. Evidence based on the radial velocity data of three PPNe with longer periods, 88−132 days, shows clear correlations of the brightness, temperature, and size of the stars, with the stars being brightest and hottest when smallest.

7. There is a suggestion of slight differences in the pulsational properties of PPNe due to composition. However, an increased sample size is needed to make more certain claims.

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